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Determination of the Degree of Fill in a Counter-Rotating Twin Screw Extruder

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Current residence time distribution models for counter-rotating extruders are mainly developed for fully filled machines. However, in practical situations, these extruders operate under starved conditions. To overcome this missing link in the current models, this paper describes the average degree of fill in the situation of starvation. This degree of fill is determined by the length over which the extruder is fully filled and the degree of fill in the partially filled zone. The comparison of the experiments with the theory shows that the existing theory underestimates the length of the fully filled zone by about 30%. The degree of fill in the partially filled zone is well predicted by taking into account all non–pressure driven leakage flows.

INTRODUCTION

The residence time distribution in a counter-rotating twin screw extruder has been studied by various authors. In most studies, the authors have chosen to study either a closely intermeshing (1–5) or a non-intermeshing extruder (6–10). In another study (11), White *et al.* presented a model for both type of extruders. In the studies mentioned, either an extruder fully filled with a model liquid was studied or a plasticating process was investigated in which the influence of the solids transport and melting process were not clear. However, especially in reactive extrusion processes, starvation occurs with a low viscous liquid feed. In the these situations, the residence time distribution models are not directly applicable without additional information about the degree of fill in the extruder (11). This study describes in which way the degree of fill, and therefore the mean residence time can be described, thus providing the missing links for predictive modelling of starved fed extruders. Starvation of twin screw extruders is often applied, because in this situation the extruder is easier to control.

THEORY

The Counter-Rotating Twin Screw Extruder

Twin screw extruders are starved fed in most applications. As a result, a partially filled zone arises in this type of extruders. When a liquid is fed to the extruder, the situation as outlined in *Fig. 1* is obtained, where part of the extruder is not completely filled. In addition, a fully filled zone exists, which is the pump zone of the extruder. The transition from the partially to the fully filled zone takes place within one pitch, as can be proven by a mass balance over the transition zone and is shown experimentally (12).

The extruder studied is a closely intermeshing counter-rotating twin screw extruder. In this type of extruder, the channel of one screw is blocked by the flight of the other screw resulting in C-shaped chambers. Because of the rotation of the screws, the chambers move toward the die, resulting in material transport by positive displacement.

The theoretical throughput equals the number of C-shaped chambers transported per unit of time multiplied by the chamber volume:

$$Q_{th} = 2mNV_c \tag{1}$$

The extruder used possesses single thread start screws ($m = 1$). For reasons of clarity, all formulas in this paper are only valid for this value of m. A more extensive description is given by Janssen (12).

Because of mechanical clearances, the chambers are not completely closed. Leakage flows occur because of interactions between the chambers. The real volumetric throughput is therefore given by:

$$Q = Q_{th} - Q_l \tag{2}$$

in which Q_l is the sum of all leakage flows over a cross section of the extruder. Four different leakage flows can be distinguished in a counterrotating twin screw extruder: the flight gap, the tetrahedron gap, the cal-

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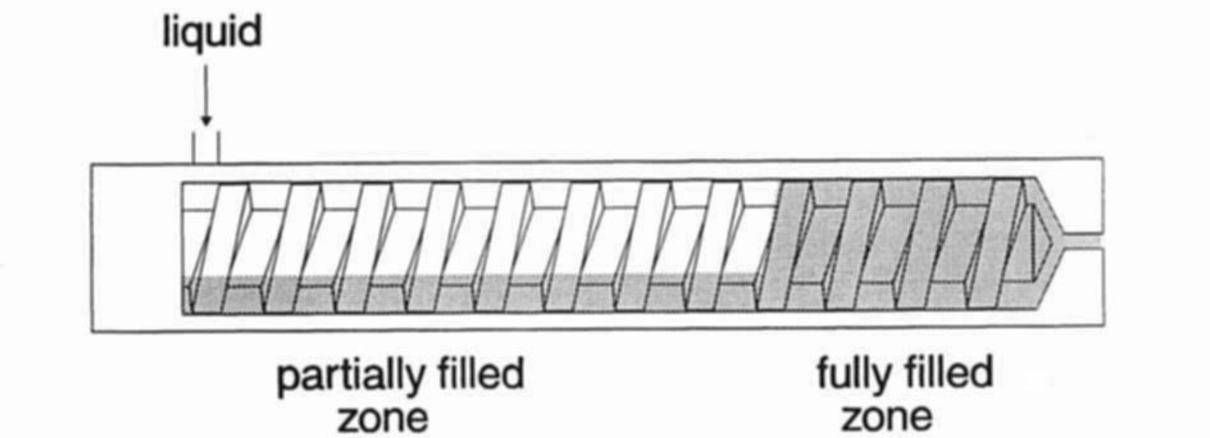

Fig. 1. Schematic representation of the two zones in an extruder, when it is fed with liquid material.

ander gap and the side gap (*Fig. 2*) The leakage flows are driven by conveying of the moving surfaces and by the interchamber pressure differences. In general form, the leakage flows equal:

$$Q_l = AN + B\frac{\Delta P_c}{\eta} \tag{3}$$

in which A and B are geometrical constants. The geometrical constants can be calculated using equations described by Janssen (12).

The Partially Filled Zone

In the partially filled zone, transport of material occurs from the feed zone to the fully filled zone. The minimum degree of fill α in the partially filled zone equals the relative throughput α_r:

$$\alpha = \alpha_r = \frac{Q}{Q_{th}} \tag{4}$$

However, when leakage flows occur in the partially filled zone, the degree of fill equals:

$$\alpha = \frac{Q + Q_{l,pfz}}{Q_{th}} \tag{5}$$

in which $Q_{l,pfz}$ represents the amount of leakage flow in the partially filled zone.

In the partially filled zone, only mechanical induced leakage flows will occur. The leakage flows in the partially filled zone can therefore be described as a fraction of the leakage flows occurring in the fully filled zone:

$$Q_{l,pfz} = \zeta AN \tag{6}$$

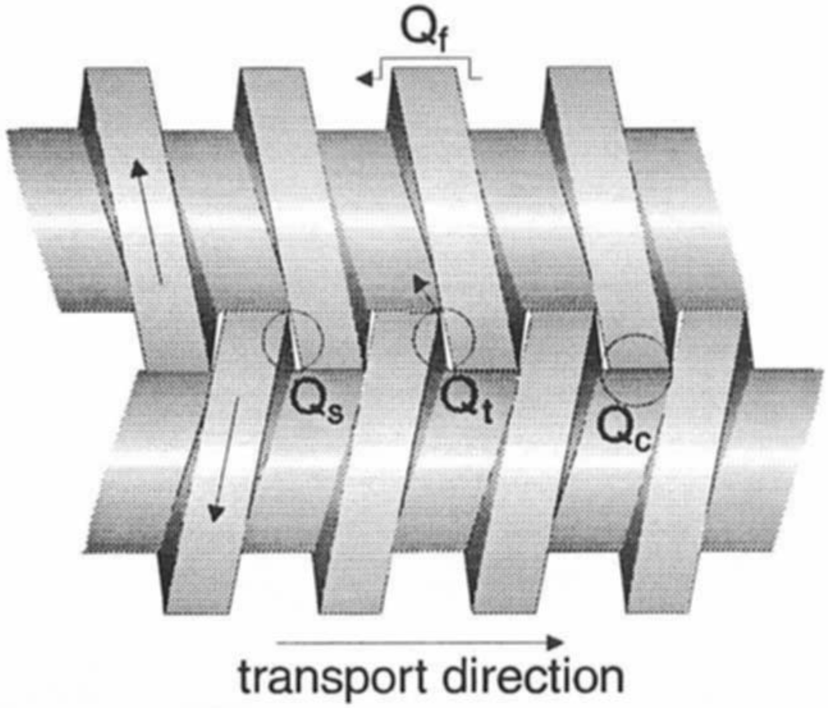

Fig. 2. The four gaps through which leakage flows occur.

In literature, several assumptions have been made for the fraction of the leakage flows that occurs in the partially filled zone. Janssen (1) assumed $\zeta = 0$ in the case of a solid feed. For most solid feeds, this assumption is valid, although Chen (4) found that for polystyrene some leakage flow occurs in the partially filled feed zone. For a liquid feed, some leakage flow will always occur, as a result of which the degree of fill is underestimated by using $\zeta = 0$.

This correction factor ζ is dependent on the degree of fill and for low viscous liquids also gravity can influence ζ. If gravity force is dominant, material in the extruder will stay on the bottom of the barrel house, which prevents material to enter other gaps than the flight gap (*Fig. 2*). This effect can reduce the amount of leakage flow in the partially filled zone. Especially in counterrotating twin screw extruders, the influence of gravity can become important because of the relatively low screw rotation rate. A dimensionless number that describes the aforementioned effect is defined by Todd (13) as the Jeffrey-number. It equals:

$$Je = \frac{gravity\ forces}{viscous\ forces} = \frac{D\rho g}{\eta N} \tag{7}$$

The Fully Filled Zone

The fully filled zone is the pump zone of the extruder. In this zone, pressure is built up, which is needed to overcome the die resistance. The length of the fully filled zone L can be calculated by means of the number of fully filled chambers υ_f. For an isoviscous liquid, the pressure built up per chamber is constant, which implies:

$$\upsilon_f = \frac{P_{die}}{\Delta P_c} \tag{8}$$

The die pressure P_{die} is determined by the die resistance (K^{-1}), throughput Q, and viscosity η of the material inside the die:

$$P_{die} = \frac{Q\eta}{K} \tag{9}$$

By combining *Equations 2, 3, 8* and *9*, the number of fully filled chambers can be expressed as a function of geometrical constants, screw speed and throughput:

$$\upsilon_f = \frac{BQ}{K(Q_{th} - Q - AN)} \tag{10}$$

EXPERIMENTAL

The extruder used for the residence time measurements is a counter-rotating closely intermeshing twin screw extruder (Rollepaal). It possesses single threat start screws with a diameter of 40 mm and a uniform pitch of 24 mm. Its L/D is 15. The geometrical constant A equals 4.4×10^{-6} m^3, while B equals 1.8×10^{-9} m^3. To the extruder, one of the dies listed in *Table 1* is attached. The screw rotation rate can be varied from 0 to 0.83 s^{-1}. The total number of chambers from the injection point to the die is 22 on each screw. The volume V_c of one chamber is 7.31×10^{-6} m^3.

Table 1. The Dies Used for Residence Time Measurements. A Higher Die Number Corresponds to a Higher Die Resistance.

Die	Reciprocal Die Resistance K (10^{-11} m^3)	Die Volume (10^{-6} m^3)
I	61.9	37.3
II	4.60	31.5
III	1.52	31.1

The residence time was determined by using glycerol at room temperature, which is a Newtonian liquid with a viscosity of 0.9 Pa s. The tracer was a solution of 2.62 mmol/l Congo Red (from Merck) in glycerol. When the extrusion process had reached steady state, about 1 ml of the tracer solution was injected into the extruder at the feed end. Every 10 to 15 seconds, samples were taken at the die end in disposable cuvettes (Griener Labortechnik Kuvetten Makro), until a few minutes after all colour had disappeared in the extrudate. The absorption of the samples was measured at a wavelength of 511.5 nm using a Philips PU 8730 UV/VIS scanning spectrophotometer.

The residence time could be reproduced within 4% limits. Besides almost all tracer could be detected, which indicates that no dead zones existed in the extruder.

RESULTS

The Partially Filled Zone

To determine the degree of fill in the partially filled zone, die I was applied. The resistance of this die was chosen in such a way that according to *Equation 10* less than 1 chamber was fully filled in order to focus on the partially filled zone only. The results of the experiments are given in *Table 2*.

Table 2 shows that the degree of fill α in the partially filled zone was significantly larger than the relative throughput α_r. This implies that a certain amount of leakage flow occurs in the partially filled zone. The measurements in this study indicate that a value of $\zeta = 0.7$ predicts the degree of fill quite well (*Fig. 3*). However, for the throughput of 98 g/min, the degree of fill is underestimated, which indicates that almost all non-pressure driven leakage flows should be taken into account to obtain a better prediction.

Table 2. The Degree of Fill in the Partially Filled Zone. The Column at the Right Indicates the Percentage of Tracer Found Back in the Extrudate; τ Stands for the Mean Residence Time of the Material Inside the Extruder.

Q (g/min)	N (s^{-1})	τ (s)	υ_f (−)	α_r (−)	α (−)	% Tracer
29	0.50	213	0.2	0.07	0.25	98
30	0.83	176	0.1	0.04	0.24	101
49	0.83	144	0.2	0.07	0.29	96
62	0.50	135	0.6	0.14	0.33	
98	0.50	114	1.0	0.23	0.45	

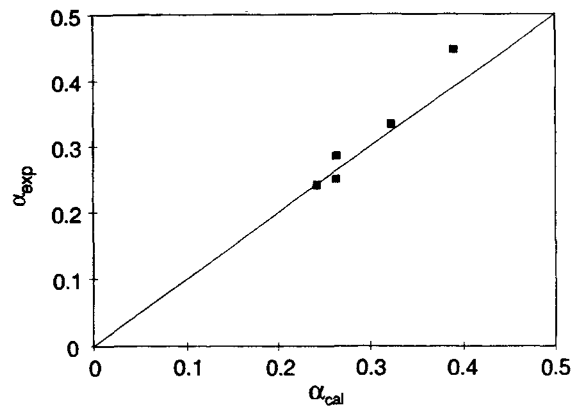

Fig. 3. The calculated degree of fill versus its experimental value for $\zeta = 0.7$.

The Influence of Gravity on the Amount of Leakage Flow in the Partially Filled Zone

By increasing the screw rotation rate, the influence of the gravity force will reduce (*Equation 7*). Therefore, by investigating the overall degree of fill as function of the screw rotation rate, the influence of the gravity force can be studied.

According to theory, a constant hold-up will be obtained when the ratio of throughput and screw rotation rate remains constant during the experiment. Therefore, not only the screw speed but also the throughput was changed in order to maintain this constant relative throughput (see *Table 3*). *Figure 4*, which is derived from the results in *Table 3*, shows that the degree of fill increases when the screw speed is increased. It can be seen that the increase in hold-up levels off at a higher screw speed, suggesting an asymptotic value for the degree of fill. The horizontal line in the figure indicates the value for the hold-up when $\zeta = 1$, which means that all non-pressure driven leakage flows are taken into account. The line therefore refers to the highest possible value for the hold-up. It seems that when the gravity force can be neglected, the total leakage flow *AN* should be taken into account. If the extrapolation is correct, the influence of the gravity is negligible at a screw speed of about 3.3 s^{-1} (200 rpm) or higher. This means that the gravity force can be neglected when:

$$Je < 150 \tag{11}$$

In most industrial extruders, the materials processed will have a greater viscosity than glycerol as a result of which the Jeffrey-number will be lower than 150. Besides, these extruders will operate at high relative throughput, which also increases the amount of leakage flow. This implies for most practical situations of plasticating extruders that for a good estimation of the degree of fill in the partially filled zone, the total amount of non-pressure driven leakage flow should be taken into account ($\zeta = 1$). However, for reactive extrusion processing, operating with low viscous monomers in the feed zone, ζ can be much smaller than unity.

Table 3. Experiments Used for the Determination of the Influence of the Gravity Force. Die II Was Attached, Resulting in Four Fully Filled Chambers.

Q (g/min)	N (s^{-1})	τ (s)
9.3	0.17	498
20.0	0.33	346
29.2	0.50	263
39.8	0.67	212
50.4	0.83	176

The Number of Fully Filled Chambers

The number of fully filled chambers can be predicted theoretically by using *Equation 10*. By applying dies with different resistances, the number of fully filled chambers can also be determined experimentally. *Figure 5* shows the principle of the measurements. According to *Equation 10*, the number of fully filled chambers is less than 1 when die I is used. When die II or III is applied, a certain number of chambers is completely filled. The number of fully filled chambers can be calculated by comparing the mean residence time obtained by die I and the mean residence time of the experiments with die II or III. The degree of fill in the partially filled zone is determined in a previous section, and is assumed to be independent of the number of fully filled chambers.

Table 4 shows the results of the experiments. From the results in the *Table*, the number of fully filled chambers can be determined and compared to theory. *Figure 6* shows this parity plot. The number of fully filled chambers, which is predicted by *Equation 10* is less than the number of chambers determined experimentally. When the calculated number of chambers is increased with 30%, the experimental and calculated values correspond rather well. It is plausible that this discrepancy originate from the determination of the leakage flow through the tetrahedron gap. Especially, the local pressure differences around this gap are difficult to describe and is probably higher than the

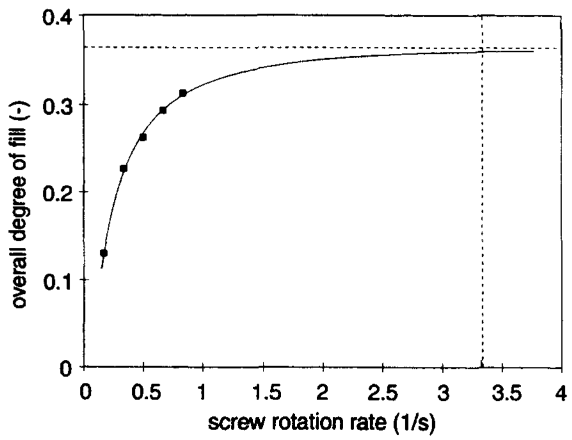

Fig. 4. The effect of the screw speed on the overall hold-up at constant relative throughput. Die II was attached, resulting in four fully filled chambers.

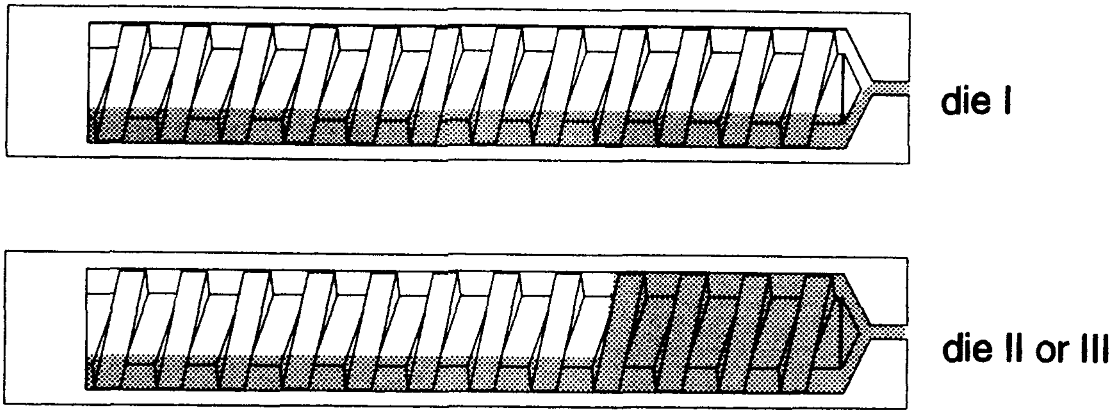

Fig. 5. An extruder with and without fully filled chambers.

average pressure difference in adjacent chambers, which is used in the description of the leakage flow through the tetrahedron gap (12). However, although the difference between calculated and experimentally determined number of fully filled chambers is not completely understood yet, the fact that the difference can be described by a single correction factor of 1.3 makes it possible to continue with applying the current description of the leakage flows and residence time distribution models.

CONCLUSIONS

The mean residence time in a counter-rotating twin screw extruder is determined by the throughput, the degree of fill in the partially filled zone, and the number of fully filled chambers.

The experiments, in which the residence time is measured, show that the number of fully filled chambers is by about 30% underestimated by the traditional extruder theory. Besides, the experiments show that a good prediction of the degree of fill in the partially filled zone for low viscous liquids can be obtained by taking into account 70% of non-pressure driven leakage flows. For industrial plasticating extrusion processes however, all total non-pressure driven leakage flows should be taken into account.

Table 4. Experiments Used for the Determination of the Number of Fully Filled Chambers. The Last Column Indicates the Percentage of Tracer Found Back in the Extrudate.

Exp. No.	Die	Q (g/min)	N (s^{-1})	τ (s)	α (–)	% Tracer
1	I	29.3	0.50	213	0.25	98
2	II	29.2	0.50	263		98
3	III	29.6	0.50	370		98
4	I	61.7	0.50	135	0.33	
5	II	60.0	0.50	200		97
6	III	60.0	0.50	326		108
7	I	98.0	0.50	114	0.45	
8	II	99.7	0.50	169		
9	III	98	0.50	263		98
10	I	29.5	0.83	176	0.24	101
11	II	29.7	0.83	226		
12	I	48.9	0.83	144	0.29	96
13	II	50.4	0.83	176		

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NOMENCLATURE

A	geometrical constant for the non-pressure driven leakage flows	m^3
B	geometrical constant for the pressure driven leakage flows	m^3
D	diameter of the screw	m
g	gravity force constant	m/s^2
Je	Jeffrey number	—
K	reciprocal die resistance	m^3
m	number of thread starts	—
N	screw rotation rate	s^{-1}

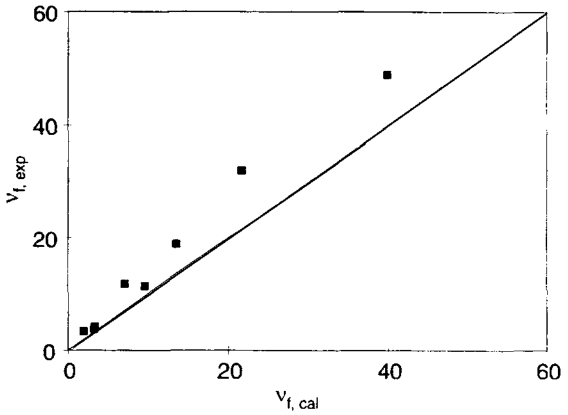

Fig. 6. Parity plot of the number of fully filled chambers without correction.

ΔP_c	pressure difference of two adjacent chambers	Pa
P_{die}	die pressure	Pa
Q	throughput	m^3/s
Q_l	total leakage flow	m^3/s
$Q_{l,pfz}$	leakage flow in the partially filled zone	m^3/s
Q_{th}	theoretical throughput	m^3/s
V_c	volume of a C-shaped chamber	m^3
α	degree of fill	—
α_r	relative throughput	—
η	viscosity	Pa s
ρ	density	kg/m^3
υ_f	number of fully filled chambers	—
ζ	fraction of leakage flow occurring in partially filled zone	—

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